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THERMAL PROPERTIES OF THE SOIL AS A FUNCTION OF ITS MOISTURE AND COMPACTNESS

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ABSTRACT. Heat conductivity, temperature conductivity and volume heat capacity have been determined for the south chernozem as a function of its compactness and moisture.

These properties were found to vary with the stage of soil moistening. It is concluded that the mechanism of heat conductivity of moist soil depends upon the mechanism of moisture conductivity and on the character of water binding by soil particles, that is to say, the thermal properties of the given soil depend on its water properties.

Thermal properties of a soil, as we know, affect the biochemical processes occurring in it and the physiological processes in plants. /40*

Various agricultural measures such as irrigation, rolling, deep plowing, loosening may to a certain extent change the thermal characteristics of a soil. However, when applying farming techniques it is first necessary to know the thermal properties of a soil. These properties can be expressed in terms of thermal characteristics: heat conductivity, temperature conductivity, and volume heat capacity.

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*Numbers in the margin indicate pagination in the original foreign text.

The role of thermal characteristics in the creation of the necessary thermal conditions in a soil by treating it has been discussed a great deal [8, 12, 13]. However, it has not been established how the thermal characteristics vary depending on the properties of a soil.

We have determined the thermal characteristics of southern black soil and some other of its physical properties that affect the former.

The soil under study can be classified as a light clay with respect to its mechanical composition. The specific gravity of the solid phase varies from 2.5 to 2.7 g/cm^3, and the compactness — from 1.2 to 1.5 g/cm^3 in a 0 - 100 cm layer. The water constants were determined on the basis of the rate of dehumidification established by F. Ye. Kolyasev's method, and then confirmed and supplemented by field and laboratory tests. The maximum hygroscopicity was 8.1%, wilting moisture was 11, moisture at which plant growth is inhibited was 18, field moisture capacity was 27, and the total moisture capacity was 41% of the weight of dry soil.

In the present paper we give the results of an investigation of thermal characteristics of southern black soil as a function of its moisture and compactness. The experiment was conducted for soils with modified structure, since in our study it was necessary to vary compactness at constant moisture and to vary moisture at constant compactness, which under field conditions is impossible.

In recent years, Soviet specialists have developed many techniques for determining the thermal characteristics of soils [9, 11]. The temperature conductivity coefficient was determined using Kondrat'yev's method [7] which is based on the principle of regular conditions for a specimen of cylindrical shape.

Compactness ρ was experimentally varied from 1.1 to 1.5 g/cm^3 in steps of 0.1, and moisture W was classified as follows: absolutely dry, air dry, 10, 20, and 25% of weight moisture. The temperature conductivity coefficient K was measured for more than 100 specimens of the soil in the arable layer. Similar measurements were made for the 80 - 100 cm layer of the soil. These values of K differed from K for the arable layer within the limits of the measurement error. It may be concluded that for the southern black soil the temperature conductivity coefficient for the same compactness and moisture is practically constant down to the underlying rock. This is due to the fact that the soil dispersion in this layer is uniform. Therefore, in our analysis of the dependence of K on moisture and compactness we shall limit ourselves to the data pertaining to the arable layer. /41 The table gives the average values of the experimental data as a function of moisture and compactness.

Figure 1 is a plot of these data.

TABLE. TEMPERATURE CONDUCTIVITY OF SOUTHERN BLACK SOIL AS A FUNCTION OF MOISTURE AND COMPACTNESS

In %	Values of ρ				
	1,1	1,2	1,3	1,4	1,5
0	0,0012	0,0013	0,0015	0,0016	0,0017
4	0,0013	0,0015	0,0016	0,0017	0,0017
10	0,0023	0,0026	0,0027	0,0030	—
20	0,0033	0,0035	0,0038	0,0041	0,0043
25	0,0031	0,0033	0,0035	0,0037	0,0039

The volume heat capacity can be determined using the relation

$$C_\rho = \left(0{,}2 + \frac{W}{100}\right)\rho,$$

where C_ρ is the volume heat capacity; W is the moisture; ρ is the compactness; 0.2 is the specific heat capacity of heavy loamy soils.

The volume heat capacity depends linearly on moisture and compactness.

The heat conductivity coefficient λ was calculated from $\lambda = KC_\rho$. The data thus obtained are plotted in Figure 2.

The heat conductivity coefficient for any moisture and compactness can be determined using the empirical formula that we have found:

$$\lambda = 10^{-3}\left[(2{,}1\rho^{1{,}2-0{,}02W})^{1-0{,}007(W-20)^2} + \rho^{0{,}8+0{,}02W}\right)\left(0{,}2+\frac{W}{100}\right)\rho\Big].$$

This formula is very complicated, so we constructed a nomogram (2) that we can easily use to determine all thermal characteristics given moisture and compactness, and knowing K, λ, ρ we can also determine moisture.

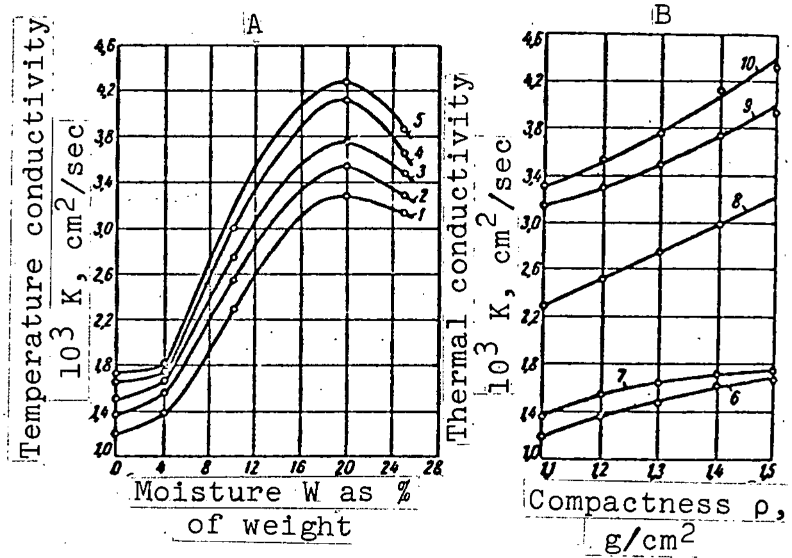

Figure 1. Temperature conductivity coefficient as a function of moisture for different degrees of compactness (A) and compactness for various degrees of moisture (B)

1 — ρ = 1,1; 2 — ρ = 1,2; 3 — ρ = 1,3; 4 — ρ = 1,4; 5 — ρ = 1,5; 6 — w = 0%; 7 — w = 4; 8 — w = 10; 9 — w = 25; 10 — w = 20%

The temperature conductivity coefficient was also determined for soils with modified structure. The values of K thus obtained are slightly lower than for soils with modified structure. For soil specimens obtained from various depths, the differences between the data obtained for a modified structure decrease with depth. If at the depth of 10 and 20 cm, the differences amount to 11%, then at the depth of 30 cm they are only 5%, which does not exceed the measurement error.

The laws of variation for K thus found for soils with modified structure may also be applied to natural conditions.

Discussion of the Experimental Results

According to the data obtained by Chudnovskiy [14], Dimo [3], Kostin [10], K = f(W) attains a maximum for different values of moisture depending on the properties of a soil. For fine lime water sand, the maximum of K lies in the region of 8 - 10% moisture, for large-grained sand — 5 - 8, and for clay — 24 - 28%.

The character of the plots of K = f(W) is also diverse: for a sandy soil the curve is convex, and for a clay soil it is concave.

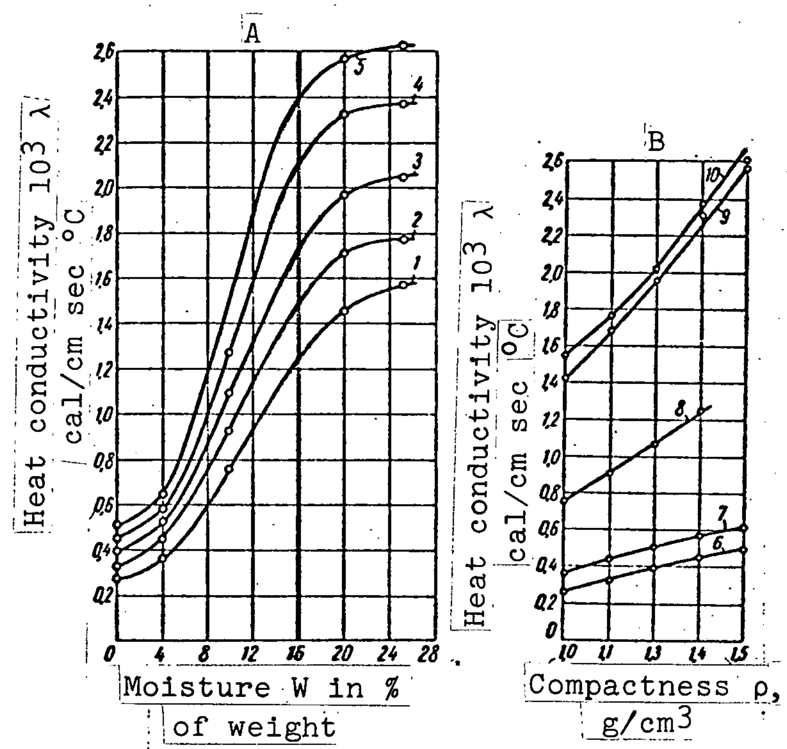

Figure 2. Heat conductivity coefficient as a function of moisture for different degrees of compactness (A) and compactness for different degrees of moisture (B)
1 — ρ = 1.1; 2 — ρ = 1.2; 3 — ρ = 1.3; 4 — ρ = 1.4; 5 — ρ = 1.5; 6 — w = 0%; 7 — w = 4; 8 — w = 10; 9 — w = 20; 10 — w = 25% /42

According to our data, obtained on the

basis of a large number of measurements at various values of compactness and moisture, K for the southern black soil attains a maximum when the moisture is 18 - 20%.

The results obtained in our experiments, as well as the data obtained by other workers, make it possible to explain the dependence of K on moisture, as being due to diverse water properties of soils. The heat conductivity and temperature conductivity coefficients for a given soil increase nonuniformly in various moisture intervals as the moisture becomes larger. This is confirmed by the nonuniform character of heat transfer for various degrees of moisture.

The view that the heat transfer mechanism depends on the form of water in the soil was advanced by Chudnovskiy [14], and by Dimo [4]. In a dry soil, as a dispersive solid-gas system, the heat flux travels not in the form of a continuous front, but in the form of individual streams in the direction of the minimum distances between particles [1]. In a moist soil, which is a three-phase medium, heat transfer is mediated by solid particles, water, and air. The magnitude of heat conductivity depends on the form, character, and the magnitude of contacts between individual particles, on on the amount of water and air between them. Therefore, in order to predict the character of heat transfer in a moist soil, it is necessary to know the character of bonding between soil particles and water for various degrees of moisture. There is no single view on this matter, which additionally hampers the explanation of how the heat is transferred through the soil.

In order to clarify the relationship between thermal characteristics and the moisture of soils, we have used the theory of the state and motion of moisture in a soil, which was developed by Kolayasev [5] and was named a theory of differential soil moisture. F. Ye. Kolyasev constructed a concept for the dominance of various mechanisms responsible for the motion of soil moisture [6]. The basis for dividing all soil moisture according to layers is due to physical causes that give rise to the transfer of water when different degrees of moisture are present in the soil. The bonding between moisture and soil particles also plays a role.

Five basic mechanisms responsible for the motion of soil moisture are known: diffusive, film, film-meniscus, capillary, and gravitational [5]. Such a representation of the motion of soil moisture permits us to construct a hypothesis of heat transfer in a moist soil as a function of the degree of moisture. /43

The functions $K = f(\rho, w)$ and $\lambda = \phi(\rho, w)$, obtained in our experiment, can be understood if we construct a scheme of the heat transfer mechanism, related to the mechanism responsible for the motion of moisture depending on the degree of moisture and compactness of a soil.

As the compactness increases, so do the temperature conductivity and heat conductivity coefficients, since their increase is dependent on moisture.

When a soil is in the absolutely dry state, K and λ increase with compactness, and the rate of their increase is greater for small values of compactness; for larger values of compactness their growth decreases (Figures 1, 2). Heat transfer in such a soil is achieved mainly through contacts between soil particles, and with an increase in compactness a certain limit of their closeness is obviously reached. The same type of variation of K and λ is observed for air-dry states of a soil, except that their values are much greater than for the absolutely dry state, since the sorbate water improves the contact somewhat.

For 10% moisture (film mechanism of water transfer) K and λ increase linearly with compactness, and their values increase sharply as compared with their values for the air-dry state. In this stage of moisture, water participates in heat transfer. The water forms bridges at points of contact between particles, along which heat transfer takes place. At 20% moisture the film- /44 meniscus mechanism of moisture transfer becomes a capillary mechanism. At this moisture level, the values of K and λ continue to increase with compactness, and become maximum for the highest values of compactness. An increase in compactness brings particles closer to each other, which reduces the length and increases the width of the bridges, i.e., thermal resistance decreases. In addition, the amount of the solid phase whose heat conductivity is approximately 5 times greater than that of water, becomes greater. Heat transfer does not occur along individual channels, and a continuous heat flux through the water and the solid phase takes place, and this heat flux plays the fundamental role in heat transfer.

At 25% moisture the capillary mechanism of water movement becomes dominant. The character of the variation of K and λ as a function of compactness is the same as for 20% moisture, except that the value of K is smaller for all values of compactness. It can be stated that, as the moisture increases in the interval where the capillary mechanism of water movement is dominant, it is no longer a connecting bridge between solid particles, but a medium in which heat is also transferred. As the amount of water increases, it begins to play an important role in heat transfer, and the increase of the heat conductivity coefficient becomes slower, the latter approaching the heat conductivity of water (Figure 2). But since the volume heat capacity continues to increase with moisture, and $K = \lambda/C_\rho$, then the temperature conductivity coefficient decreases with a further increase in moisture (Figure 3).

Thus, the temperature conductivity coefficient increases with moisture, and reaches a maximum for that value of moisture where the film-meniscus mechanism changes into the capillary mechanism, which corresponds to the level of moisture at which plant growth is inhibited.

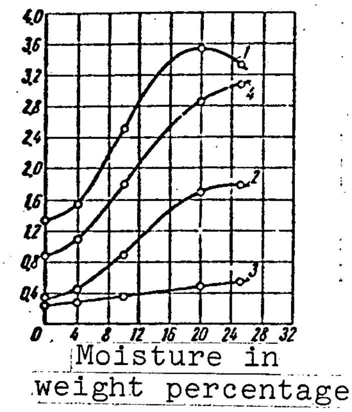

Figure 3. Thermal characteristics versus moisture for the compactness 1.2 g/cm^2

1 — temperature conductivity, 10^3 K; 2 — heat conductivity, 10^3 λ; 3 — volume capacity C_ρ; 4 — heat assimilation coefficient, 10^2 λC_ρ

Each soil is characterized by its own water constants, and this explains the fact that the temperature conductivity coefficient for various soils reaches a maximum for different degrees of moisture. Evidently, the break point of the curve $K = f(W)$ for all soils corresponds to the level of moisture at which plant growth is inhibited. There is a basis for thinking that the break points will also be observed at moisture levels corresponding to other water constants: maximum hygroscopicity and stable wilting moisture. This is a problem for further investigation which can be accomplished when a method of continuous monitoring of moisture is developed. At the present time such a method is being developed in the laboratories of the Agrophysical Institute of the All Union Academy of Agricultural Sciences im. V. I. Lenin.

Conclusions

1. The obtained dependence of thermal characteristics on moisture and compactness provides a basis for taking heat-improvement measures. Temperature conductivity, determining the heating of a soil with depth, increases with moisture up to a value at which plant growth is inhibited, and consequently, in a soil of higher moisture content the rate of temperature equalization will be greater and its heating in depth will be more /45 intensive. For moisture above the level at which plant growth is inhibited, the heating slows down since K becomes smaller.

2. Starting with the fact that the mechanism of heat transfer in a moist soil depends on the mechanism of moisture transfer for various moisture levels, we may conclude that there is a connection between the heat and the water properties of a soil.

3. An accumulation of experimental data about the dependence of thermal characteristics on moisture for various soils, simultaneously with a determination of their water properties, provides a more complete physical basis for the theory of differential moisture, which we have used to explain heat transfer in a moist soil.

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